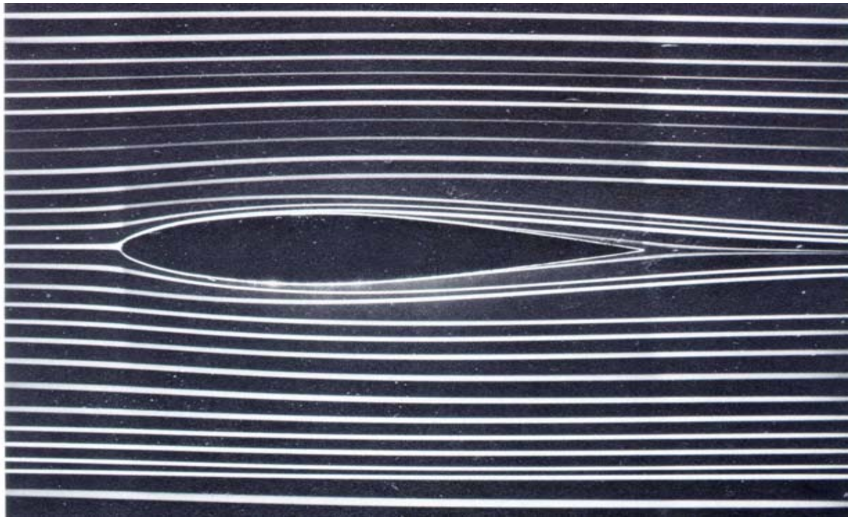
Meeting 17

Chapter 6
6-1 & 6-6

Escoamento Externo

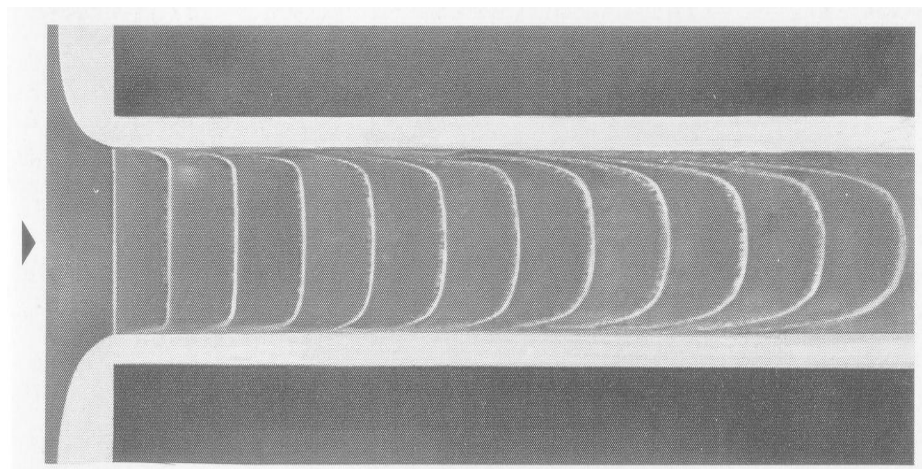
- Escoamento Externo e Interno
- Perfil de Velocidades e a lei de não deslizamento
- Tensão de cisalhamento e a Lei de Newton
- Características da Camada Limite
- Regime de Escoamento: Laminar e Turbulento
- Arrasto Viscoso
- Efeitos do Gradiente de Pressão
- Arrasto de Forma

Escoamento Externo x Interno

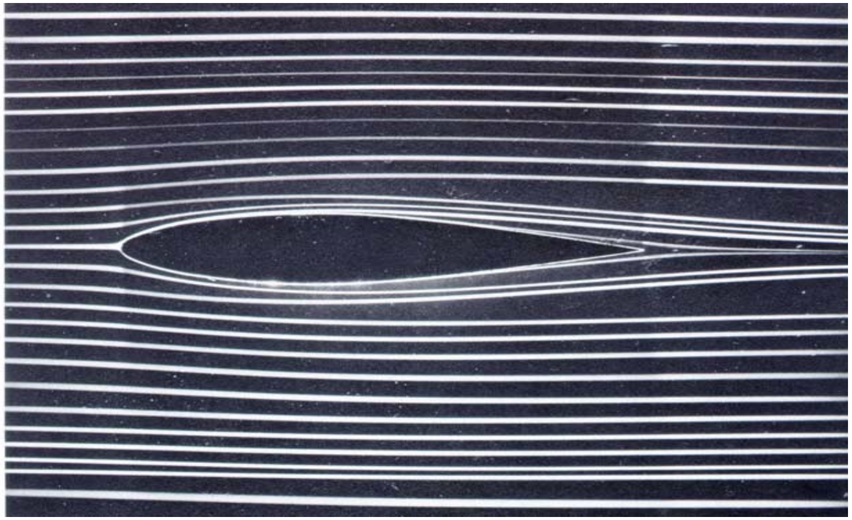


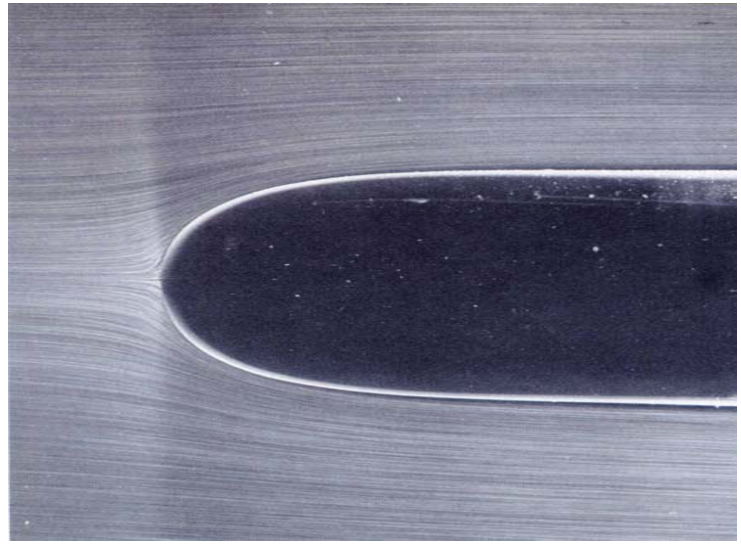
Escoamentos externos não são confinados por paredes .

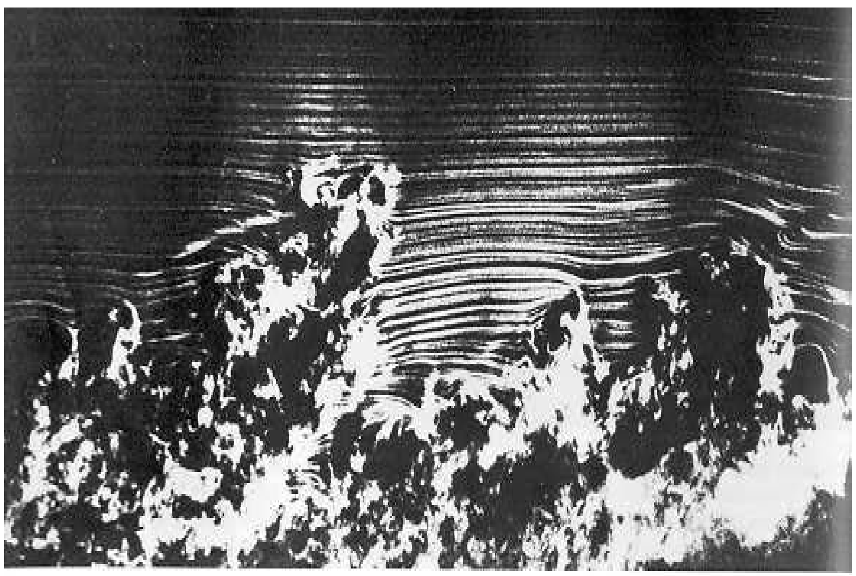
Escoamentos internos possuem fronteiras que limitam ou restringem o campo de escoamento

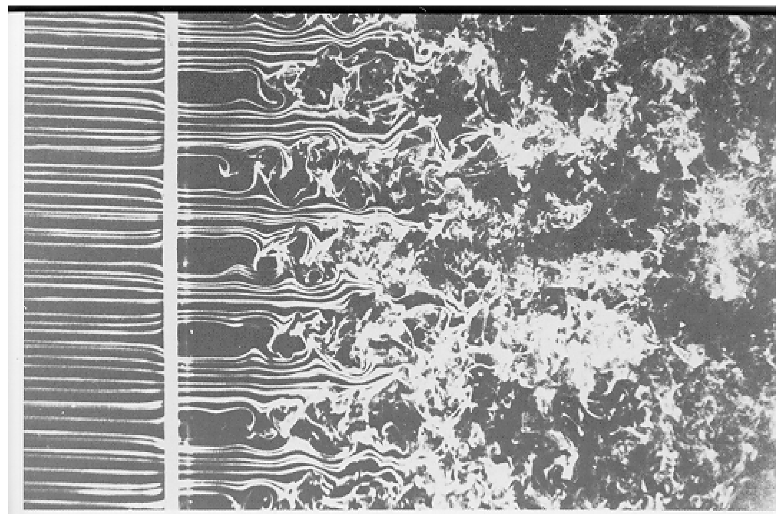


Escoamento Laminar x Turbulento









152. Generation of turbulence by a grid. Smoke wires show a uniform laminar stream passing through a $\frac{1}{16}$-inch plate with ¾-inch square perforations. The Reynolds number is 1500 based on the 1-inch mesh size. Instability of the shear layers leads to turbulent flow downstream. *Photograph by Thomas Corke and Hassan Nagib*

More Definitions

- ***Laminar flow* -- a highly ordered flow where fluid molecules follow one another in an smooth fashion.**

- ***Turbulent flow* -- disordered flow where the positions of molecules are not so easily predictable. The flow is in some sense chaotic.**
- ***Laminar or turbulent conditions greatly affect pumping power required and heat transfer rates. (We will not consider this distinction further.)***
- ***Movie: Reynolds experiment***

More Definitions

- ***Flows where density variations are unimportant are called incompressible.***

- ***In this course all our flows for fluid mechanics purposes will be incompressible.***

More Definitions

- ***A fluid moves by force or naturally.***
- ***In forced flow (forced convection) energy is added to the flow by a fan or pump or compressor that forces it to flow.***

- ***In natural flow (natural convection) natural forces such as gravity or buoyancy cause the fluid to flow.***

Perfil de Velocidades e a Lei de Não Deslizamento

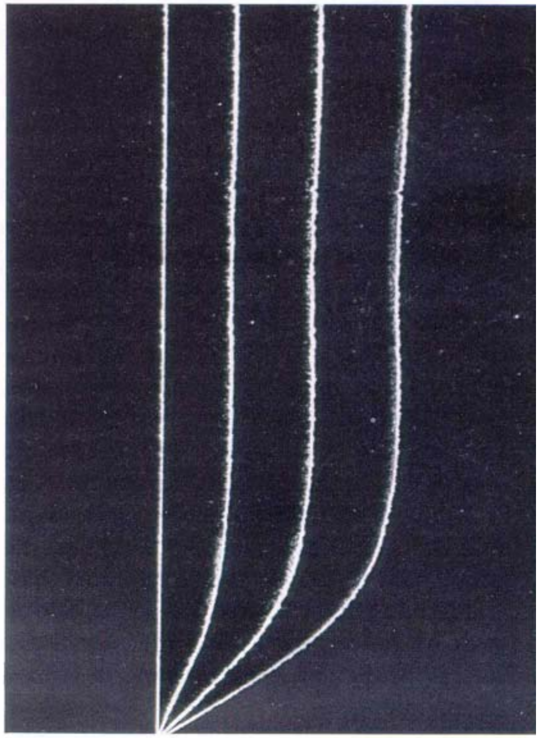


Fig. 21. Velocity profile in the laminar boundary layer (0.01% salt water, free stream velocity 0.6 cm/s, distance from the leading edge 200 mm, $Re = 1.2 \times 10^2$, hydrogen bubble method).

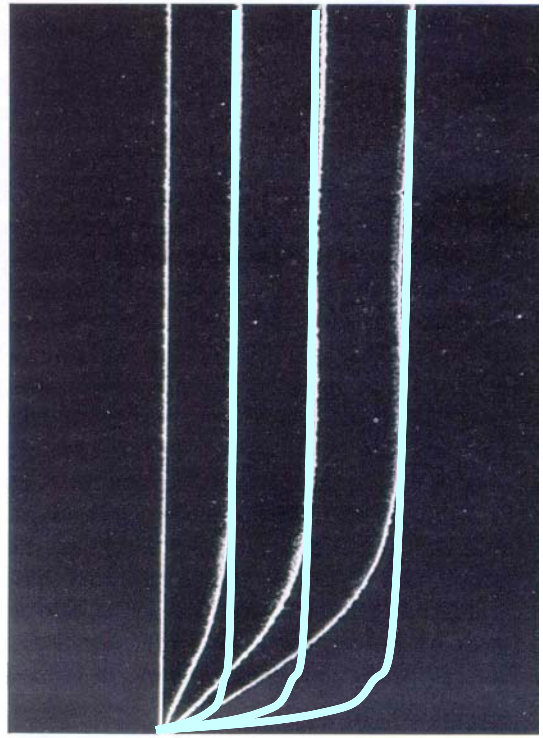


Fig. 21. Velocity profile in the laminar boundary layer (0.01% salt water, free stream velocity 0.6 cm/s, distance from the leading edge 200 mm, $Re = 1.2 \times 10^2$, hydrogen bubble method).

Perfil 'médio' de Velocidade p/ regime Turbulento

O fluido adere à parede sólida. A velocidade do fluido junto à parede é igual à velocidade da parede sólida. *No-Slip Movie*

Definition of a fluid

- ***What is the difference between a fluid and a solid?***

- ***A fluid deforms continuously when subjected to a shearing (tangential) stress, no matter how small the shearing stress.***

- ***Movie: Flow element deformation***

Shearing of a Solid (a) and a Fluid (b)

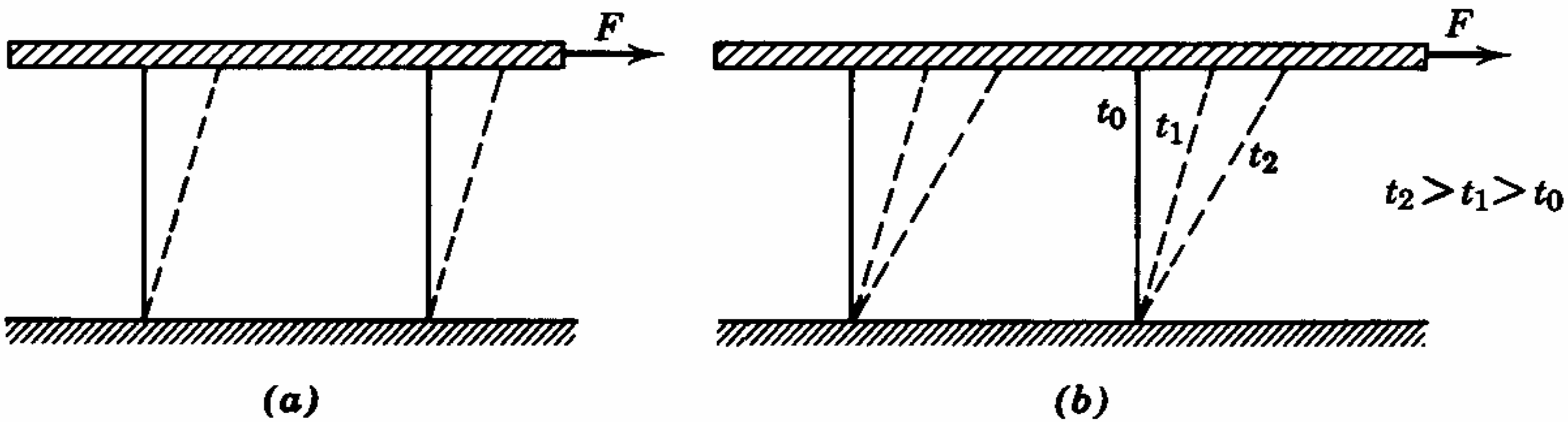


Fig. 1.1 Behavior of (a) solid and (b) fluid, under the action of a constant shear force.

The crosshatching represents (a) solid plates or planes bonded to the solid being sheared and (b) two parallel plates bounding the fluid in (b).

The fluid might be a thick oil or glycerin, for example.

Shearing of a Fluid

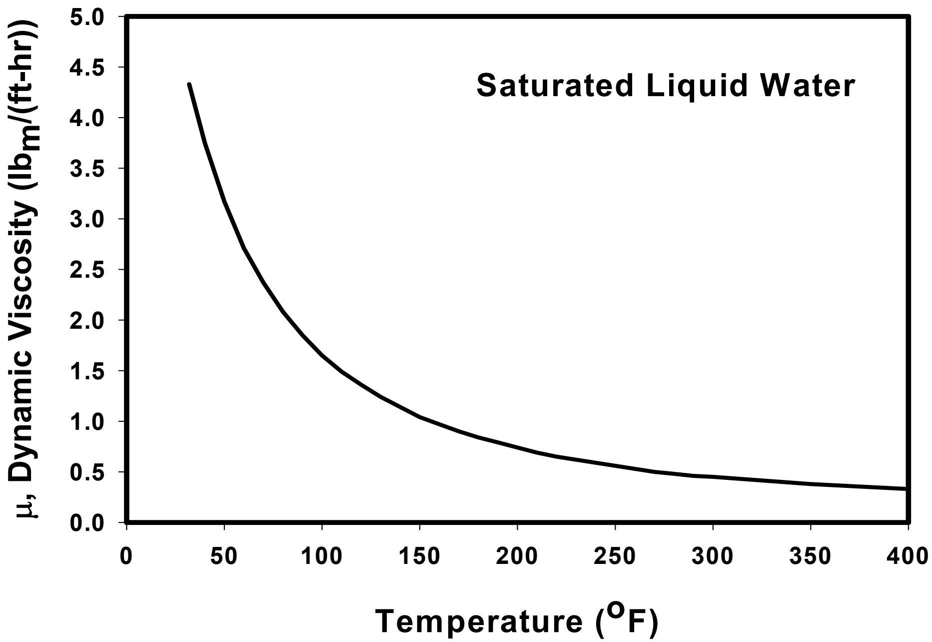
- *It can be shown that the shear stress τ is given by*

$$\tau = \mu \frac{du}{dy}$$

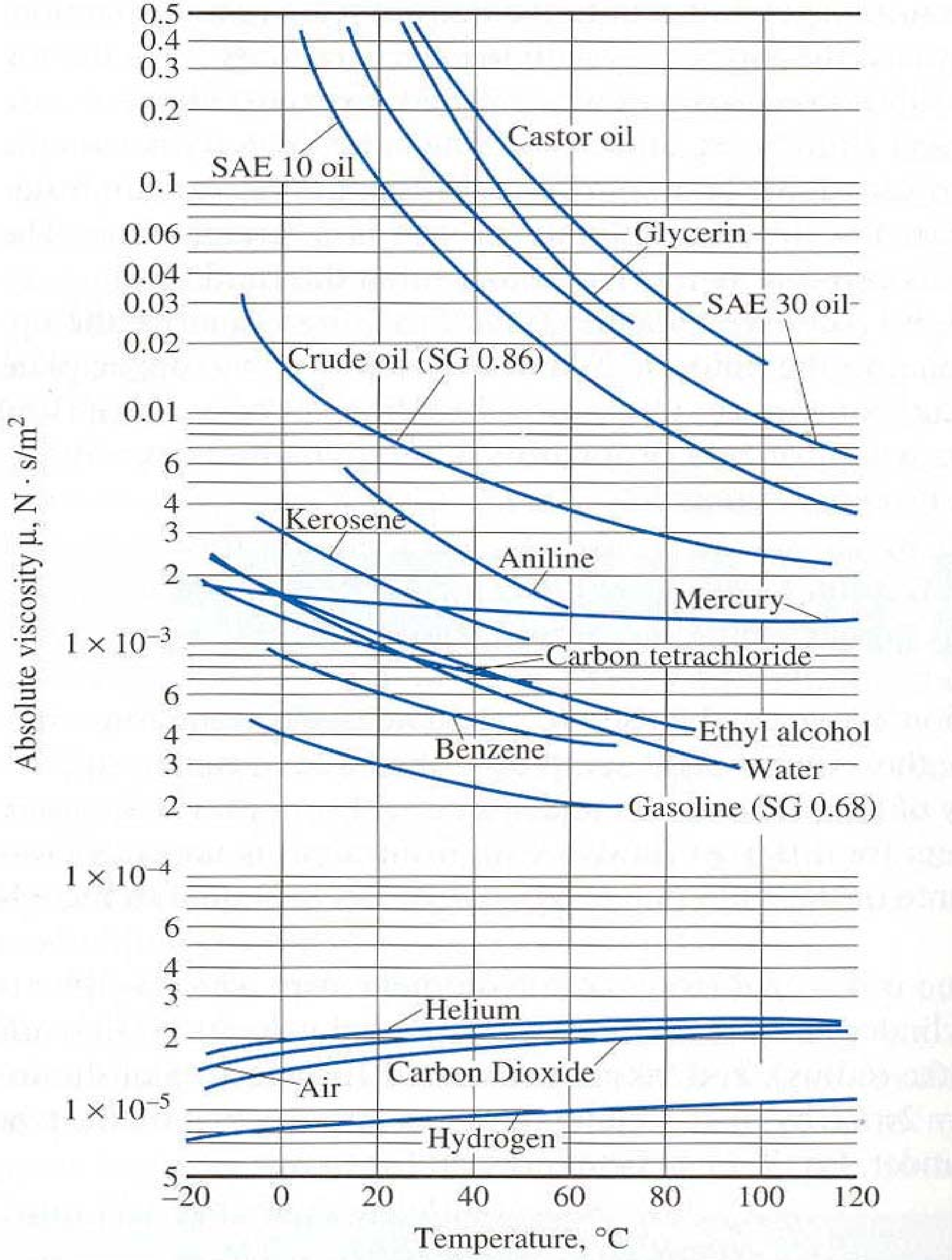
- *The term* **du/dy** *is known as the velocity gradient and as the rate of shear strain.*
- *The coefficient is the coefficient of dynamic viscosity, μ.*

Dynamic Viscosity, μ

- ***Intensive property.***
- ***Dependent upon both temperature and pressure for a single phase of a pure substance.***
- ***Pressure dependence is usually weak and temperature dependence is important.***
- ***Movie:*** *Liquid with low and high viscosity*



Dynamic viscosity of common fluids



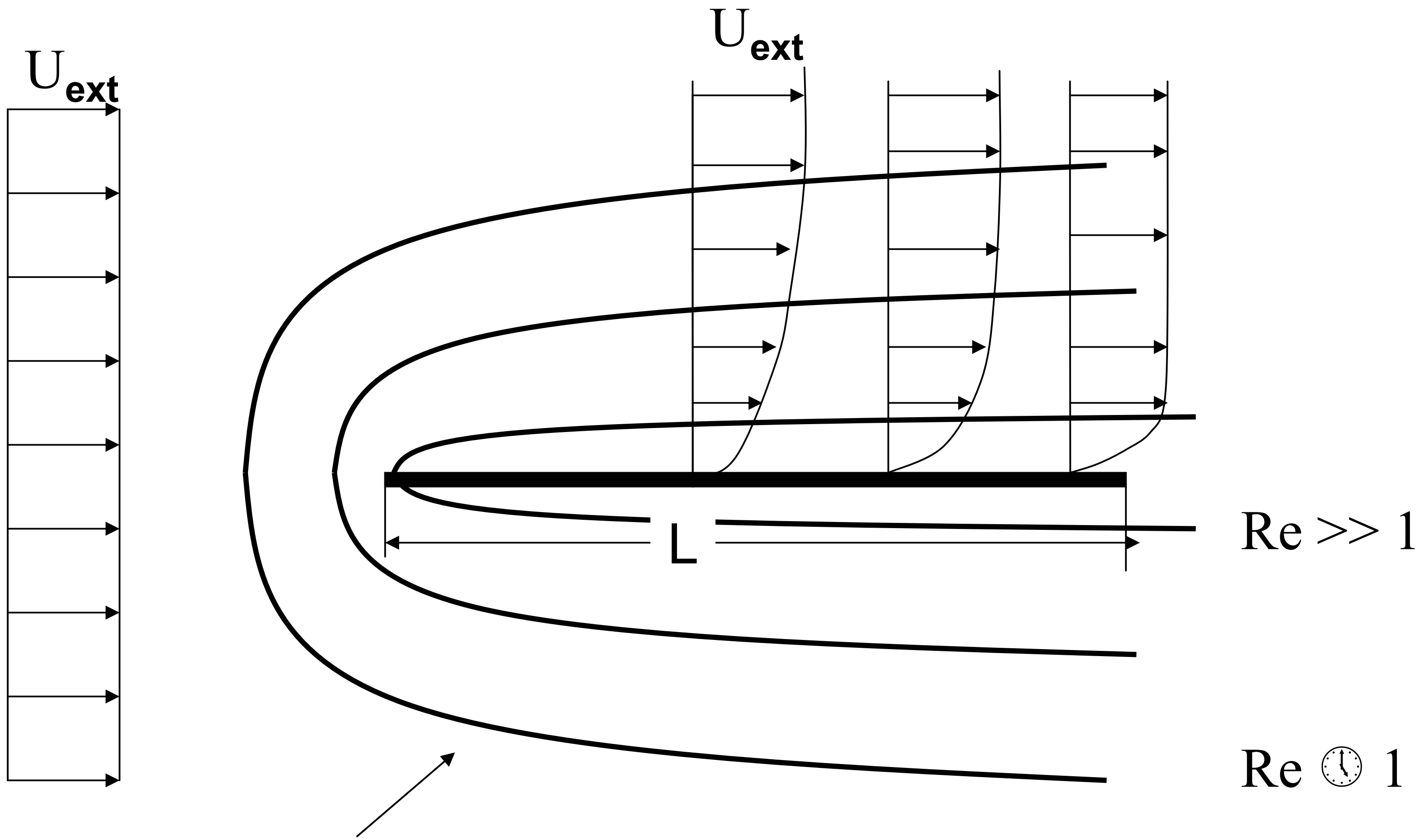
Shearing of a Fluid

- Engineering fluids are mostly Newtonian. Examples are water, refrigerants and hydrocarbon fluids (e.g., propane).

$$\tau = \mu \frac{du}{dy}$$

- Examples of non-Newtonian fluids include toothpaste, ketchup, and some paints. Non-Newtonian Movie

N. Reynolds e seu Efeito no Escoamento



Região onde predominam efeitos viscosos com presença de gradientes de velocidade, Movie

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{[\text{Termos Inerciais}]}{[\text{Termos Vis cos os}]}$$

Características da Camada Limite

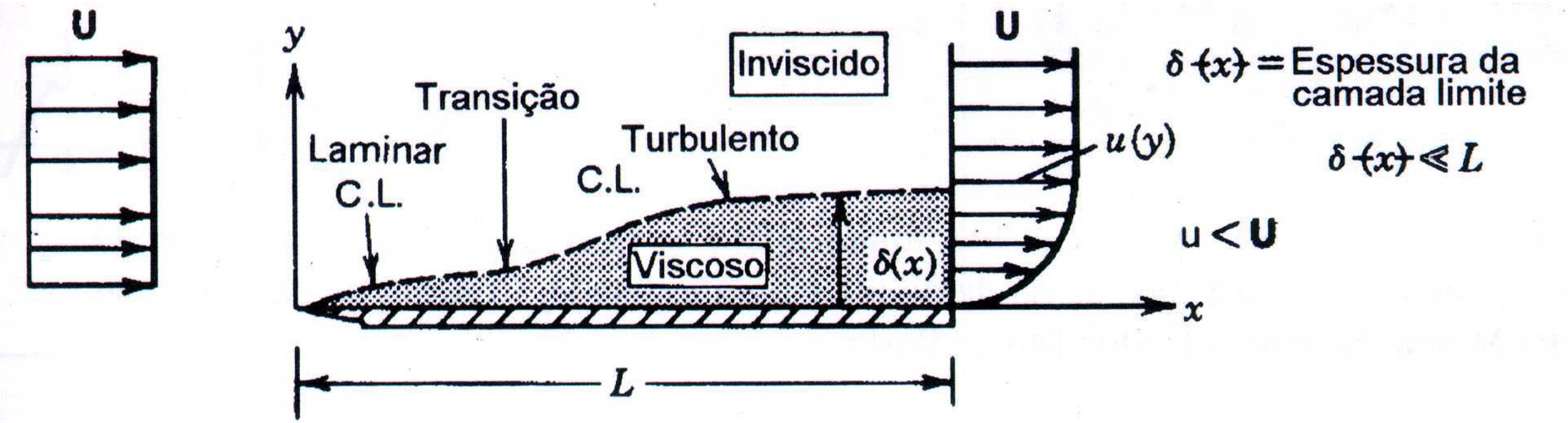


Figura 6.2 Camada limite hidrodinâmica sobre uma placa plana.

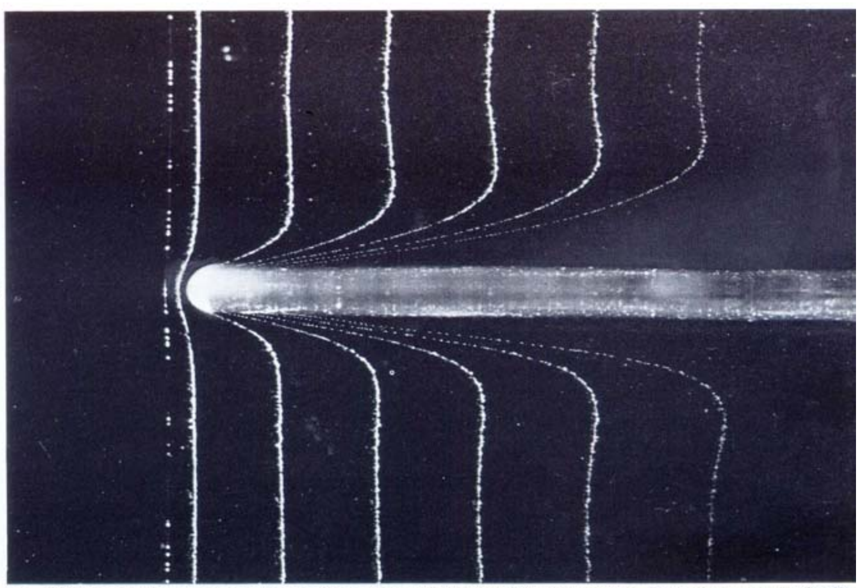


Fig. 20. Development of laminar boundary layer (0.01% salt water, free steam velocity 0.
cm/s, thickness of the plate 0.5 mm, hydrogen bubble method)

Características da Camada Limite

- **Ocorre para Re elevados, Re >> 1**

- **Perfil velocidades atinge U_{ext} para uma distância δ da parede. δ é a espessura da camada limite,δ/L <<1,**

- **A C.L. é uma região de alto gradiente de velocidade confinada próxima a parede sólida**

- **Externo a C.L. U_{ext} é governado por Bernoulli, efeitos viscosos ficam confinados na C.L.**

- **A C.L. pode ser Laminar ou Turbulenta.**

Características da Camada Limite

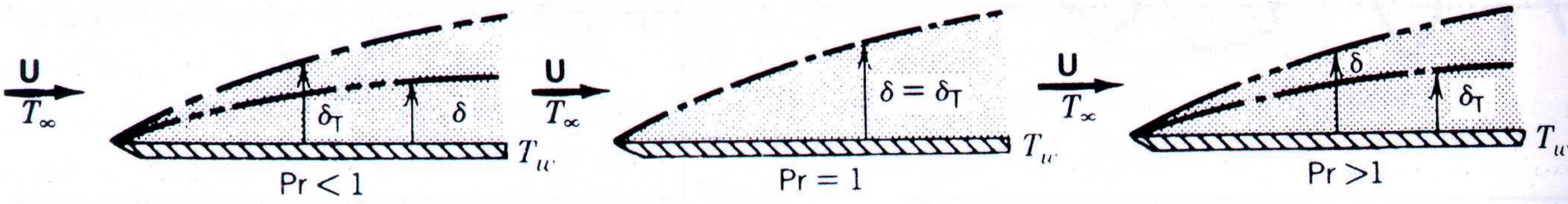


Figura 6-6 Camadas limites térmica e hidrodinâmica num escoamento sobre placa plana.

N. Prandtl, Pr

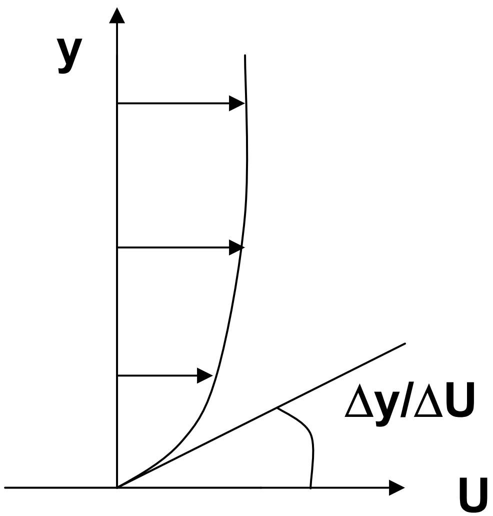
$$\mathbf{Pr} = \frac{\nu}{\alpha} = \frac{\delta}{\delta_T}$$

Onde ν é a viscosidade cinemática e α é a difusividade térmica.

O Pr pode ser interpretado como a razão entre as espessuras das C.L. Hidrodinâmica e térmica.

Arrasto Viscoso

- O arrasto viscoso é devido exclusivamente às forças viscosas que atuam nas paredes sólidas.
- A tensão de cisalhamento na parede é uma força localizada. Ela é avaliada pelo produto entre o gradiente de velocidade na parede e a viscosidade dinâmica do fluido.
- Frequentemente ela é expressa por meio do Coeficiente de Atrito, Cf, de Fanno:



$$\tau_w = \mu \left.\frac{dU}{dy}\right|_{parede} \qquad C_f = \frac{\tau_w}{(1/2)\rho U_{ext}^2}$$

$$D = \frac{1}{2}\rho U_{ext}^2 \cdot C_f \cdot [\text{Área Molhada Corpo}]$$

Arrasto Viscoso

• A força de arrasto viscoso total num corpo, é avaliada a partir da integração do arrasto localizado ao longo do corpo. Frequentemente ela é expressa em termos do coeficiente de atrito médio

$$\overline{C}_f = \frac{1}{(1/2)\rho U_{ext}^2} \frac{\int_A \tau_w \cdot dA}{A}$$

$$\overline{D} = \frac{1}{2}\rho U_{ext}^2 \cdot \overline{C}_f \cdot A$$

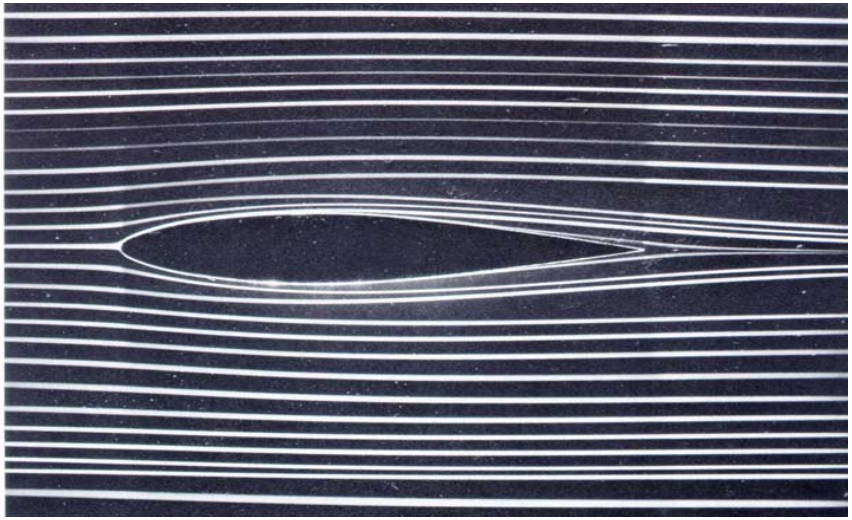
Arrasto Viscoso

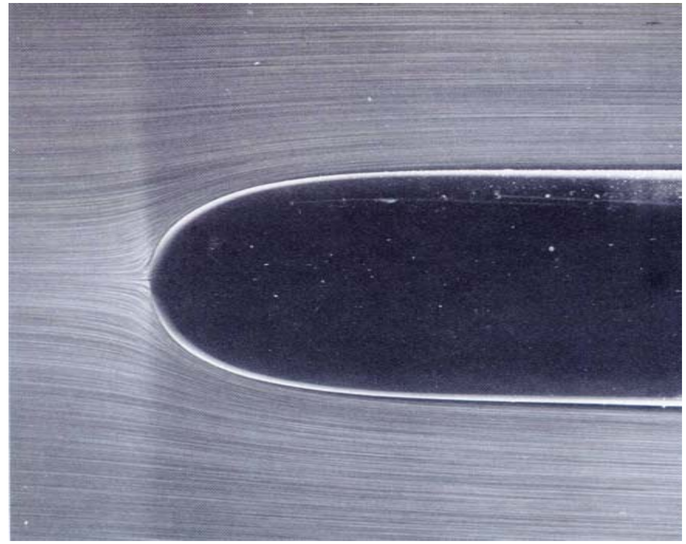
• **Arrasto viscoso em uma placa plana com ausência de gradiente de pressão:**

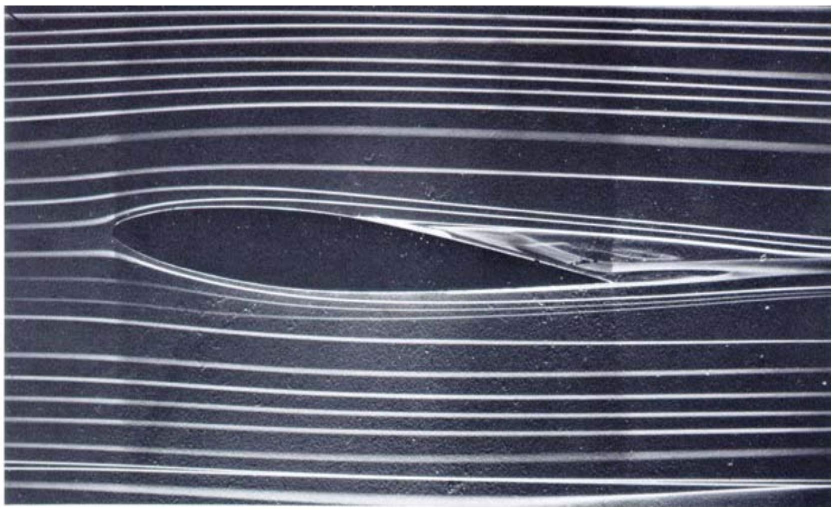
Tabela 6-1 Resumo das relações da camada limite para uma placa plana lisa

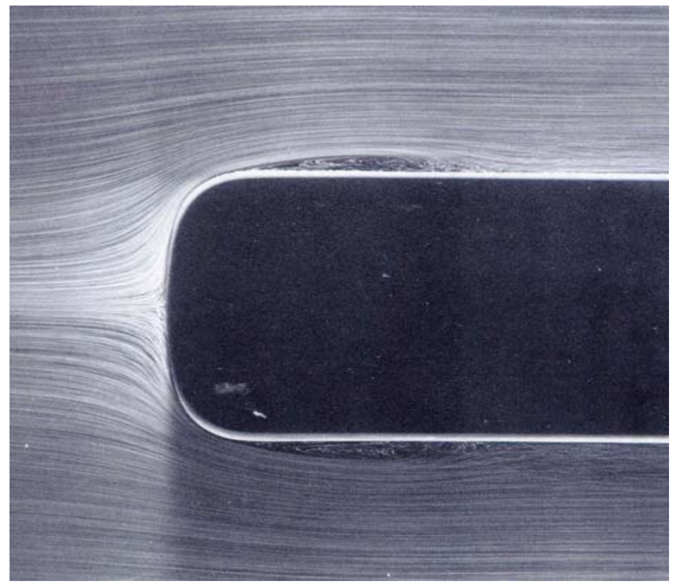
Laminar	$Re_x < 5 \times 10^5$	
$u/U = f\left(y\sqrt{U/\nu x}\right)$		Veja Tabela 6-2
$\delta / x = 5{,}0 Re_x^{-(1/2)}$		
$\tau_p = 0{,}332 \rho U^2 Re_x^{-(1/2)}$		
$C_{fx} = 0{,}664 \, Re_x^{-(1/2)}$		
$\overline{C}_f = 1{,}328 \, Re_L^{-(1/2)}$		
Turbulento	$5 \times 10^5 < Re_x < 10^7$	
$u/U \cong (y/\delta)^{1/7}$		
$\delta / x = 0{,}371 \, Re_x^{-(1/5)}$		
$\tau_p = 0{,}0296 \rho U^2 Re_x^{-(1/5)}$		
$C_{fx} = 0{,}0592 \, Re_x^{-(1/5)}$		
$\overline{C}_f = 0{,}074 \, Re_L^{-(1/5)}$		

Gradiente de Pressão & Separação

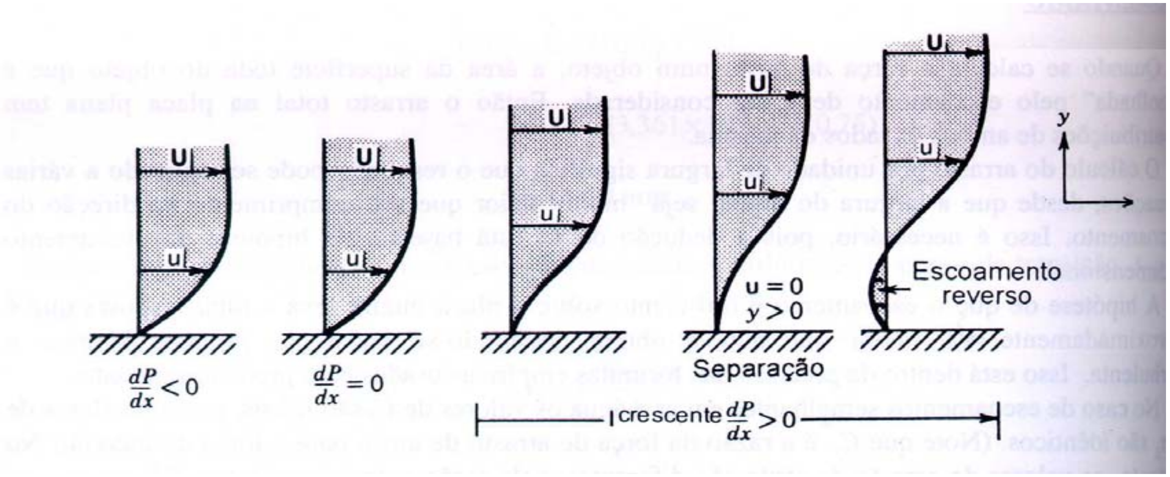








Gradiente de Pressão & Separação



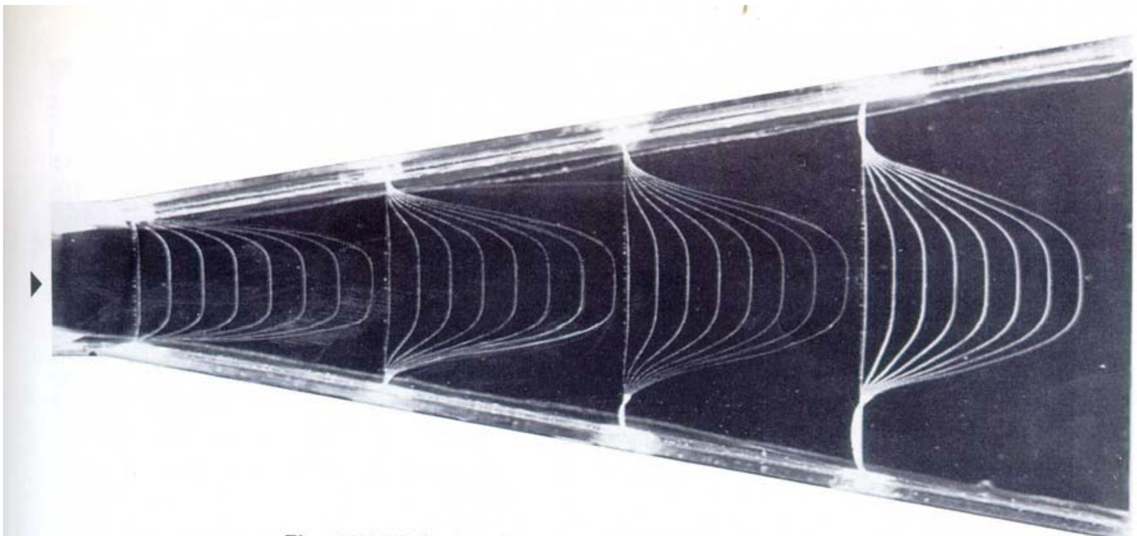
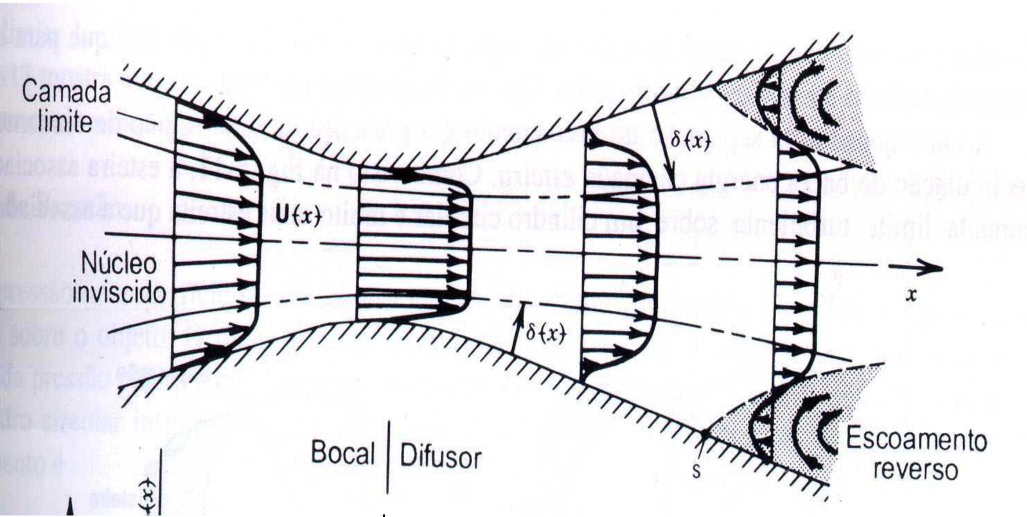


Fig. 105. Velocity distribution in a divergent passage (water, velocity = 3.0 cm/s, inlet width = 30 mm, divergence angle = 20°, *Re* = 900, hydrogen bubble method).

Gradiente de Pressão & Separação



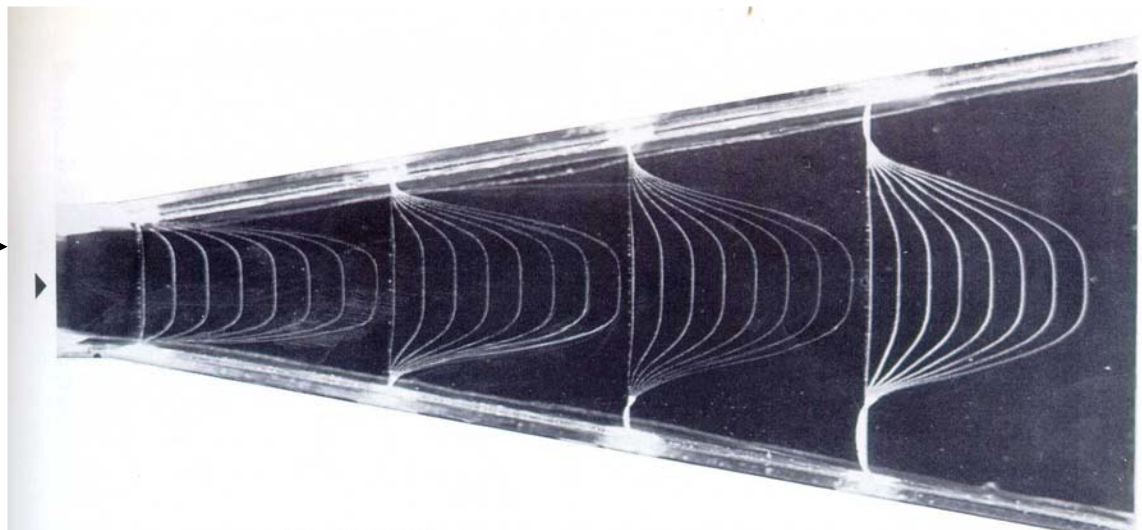
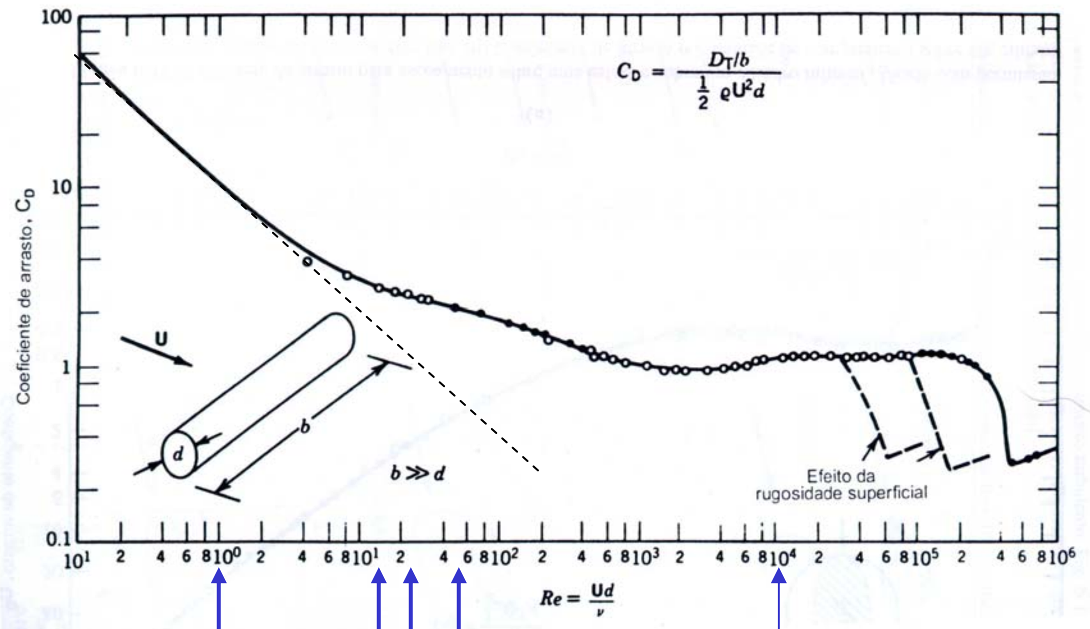
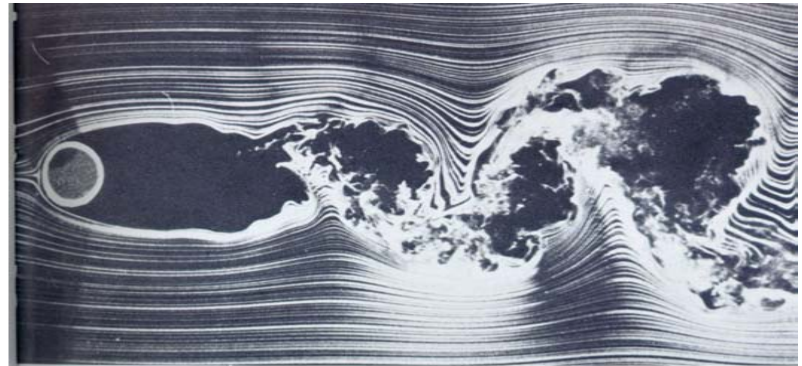


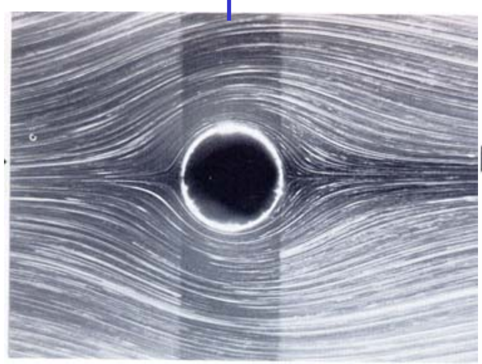
Fig. 105. Velocity distribution in a divergent passage (water, velocity = 3.0 cm/s, inlet width = 30 mm, divergence angle = 20°, *Re* = 900, hydrogen bubble method).

Cylinder Separation Movie





48. **Circular cylinder at** R=**10,000.** At five times the speed of the photograph at the top of the page, the flow pattern is scarcely changed. The drag coefficient consequently remains almost constant in the range of Reynolds number spanned by these two photographs. It drops later when, as in figure 57, the boundary layer becomes turbulent at separation. *Photograph by Thomas Corke and Hassan Nagib*



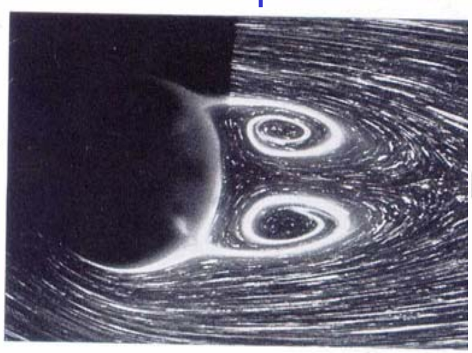


Fig. 3. Flow around a circular cylinder a = 19 (water, flow velocity 0.20 cm/s, cylir diameter 1.0 cm, aluminium pow method and electrolytic precipitat method).

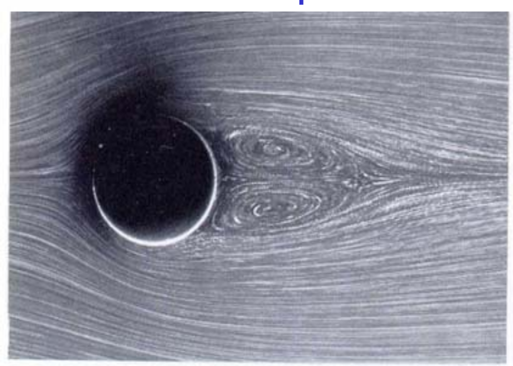


Fig. 4. Flow around a circular cylinder at *Re* = 26 (water, flow velocity 0.25 cm/s, cylinder diameter 1.0 cm, aluminium powder method).

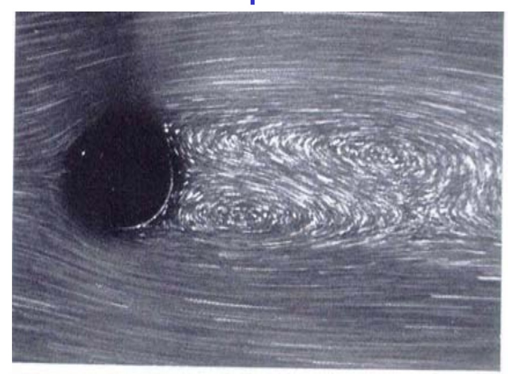


Fig. 5. Flow around a circular cylinder at *Re* = 55 (water, flow velocity 0.55 cm/s, cylinder diameter 1.0 cm, aluminium powder method).

Gradiente de Pressão & Separação

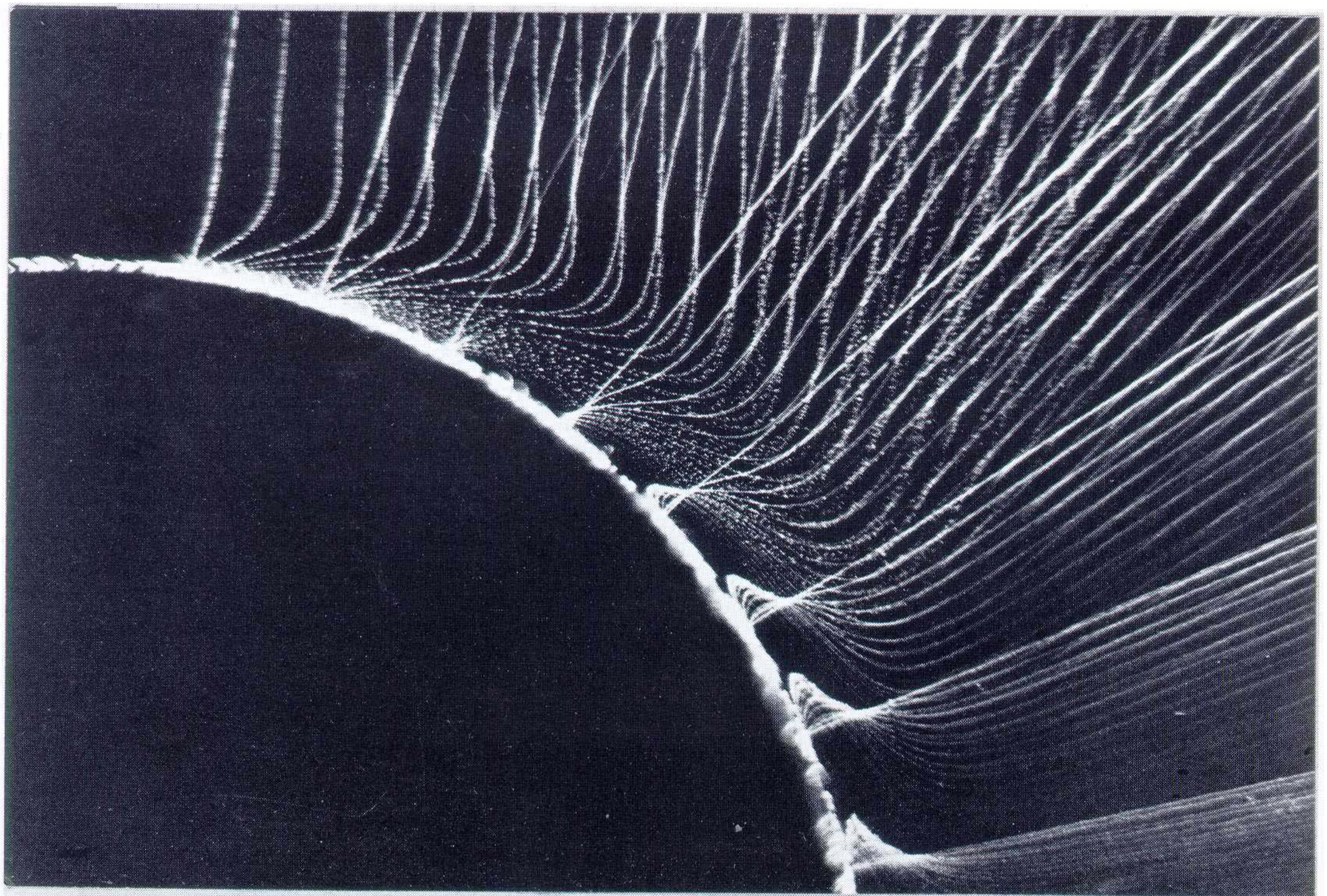


Fig. 22. Water, velocity of motion 2 cm/s, cylinder diameter 70 mm, photographed two seconds after the start of motion, $Re = 1.2 \times 10^3$, hydrogen bubble method.

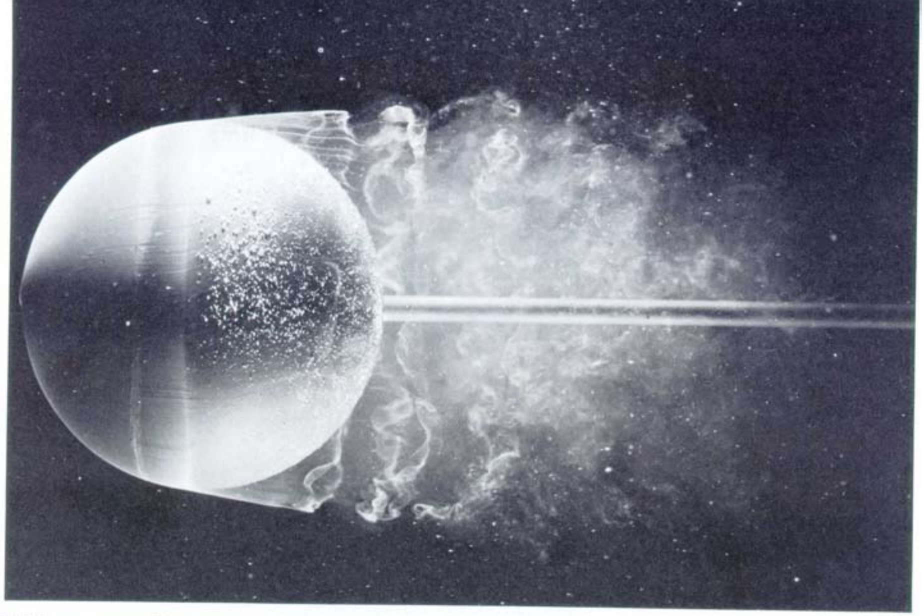
A Distribuição de Pressão no Corpo Causa uma Força Resultante Contrária ao Escoamento?

A Separação (Descolamento) do Escoamento Altera a Distribuição de Pressão no Corpo?

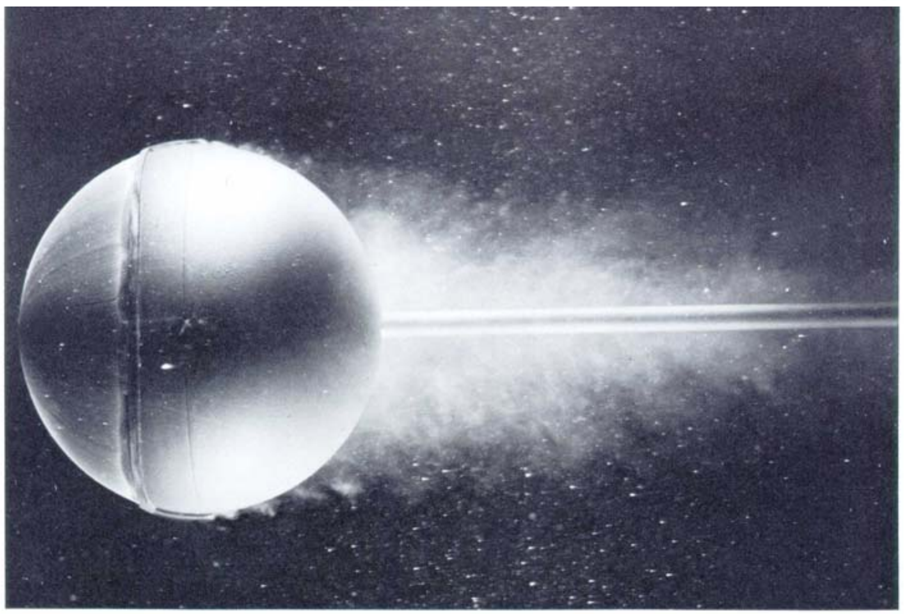
Ela Tem Influência na Força de Arrasto do Corpo?

Arrasto de Forma (Distribuição de Pressão)

Bluffy Body Movie



55. Instantaneous flow past a sphere at R=15,000. Dye in water shows a laminar boundary layer separating ahead of the equator and remaining laminar for almost one radius. It then becomes unstable and quickly turns turbulent. *ONERA photograph, Werlé 1980*



57. Instantaneous flow past a sphere at R=30,000 with a trip wire. A classical experiment of Prandtl and Wieselsberger is repeated here, using air bubbles in water. A wire hoop ahead of the equator trips the boundary layer. It becomes turbulent, so that it separates farther rearward than if it were laminar (opposite page). The drag is thereby dramatically reduced, in a way that occurs naturally on a smooth sphere only at a Reynolds number ten times as great. *ONERA photograph, Werlé 1980*

Distribuição de Pressão Não Simétrica Em Cilindros

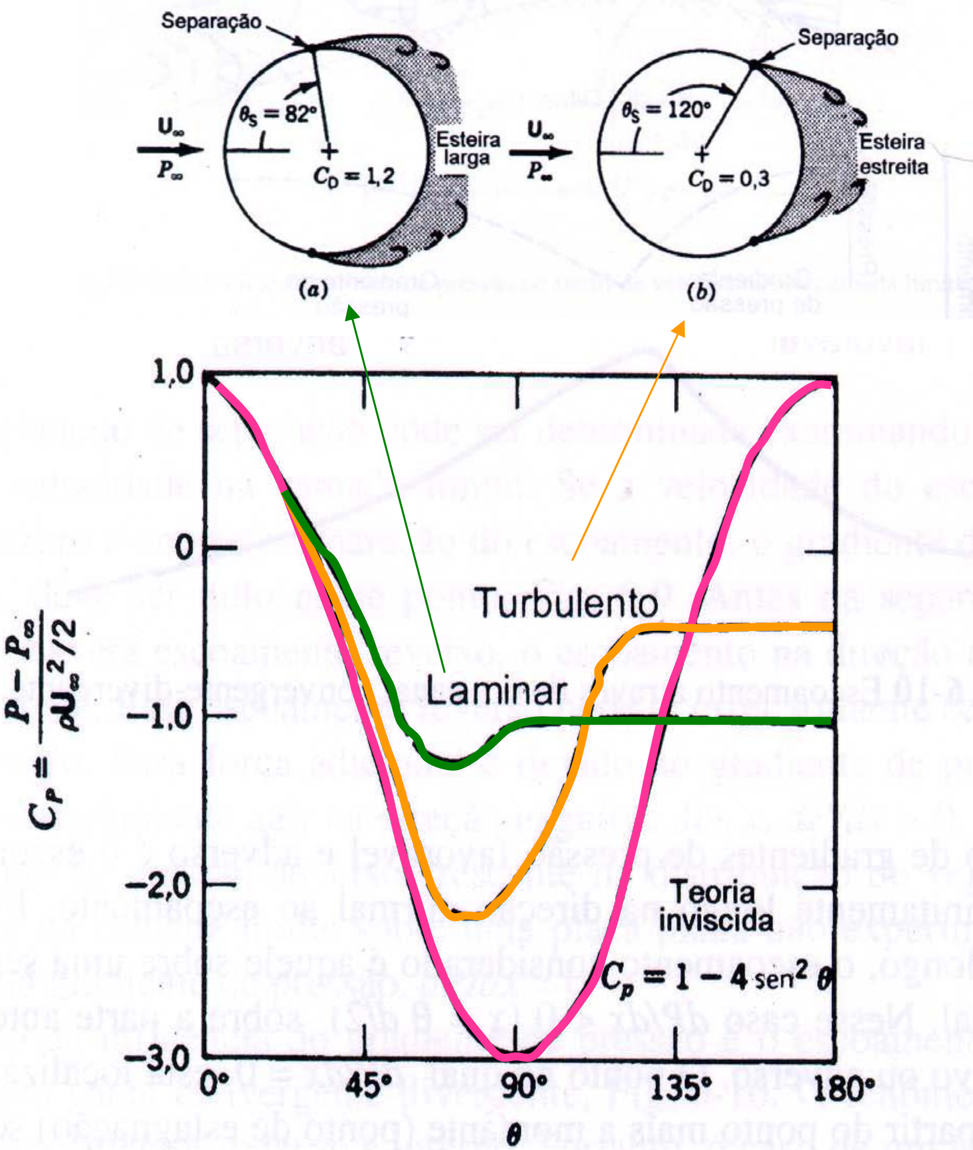
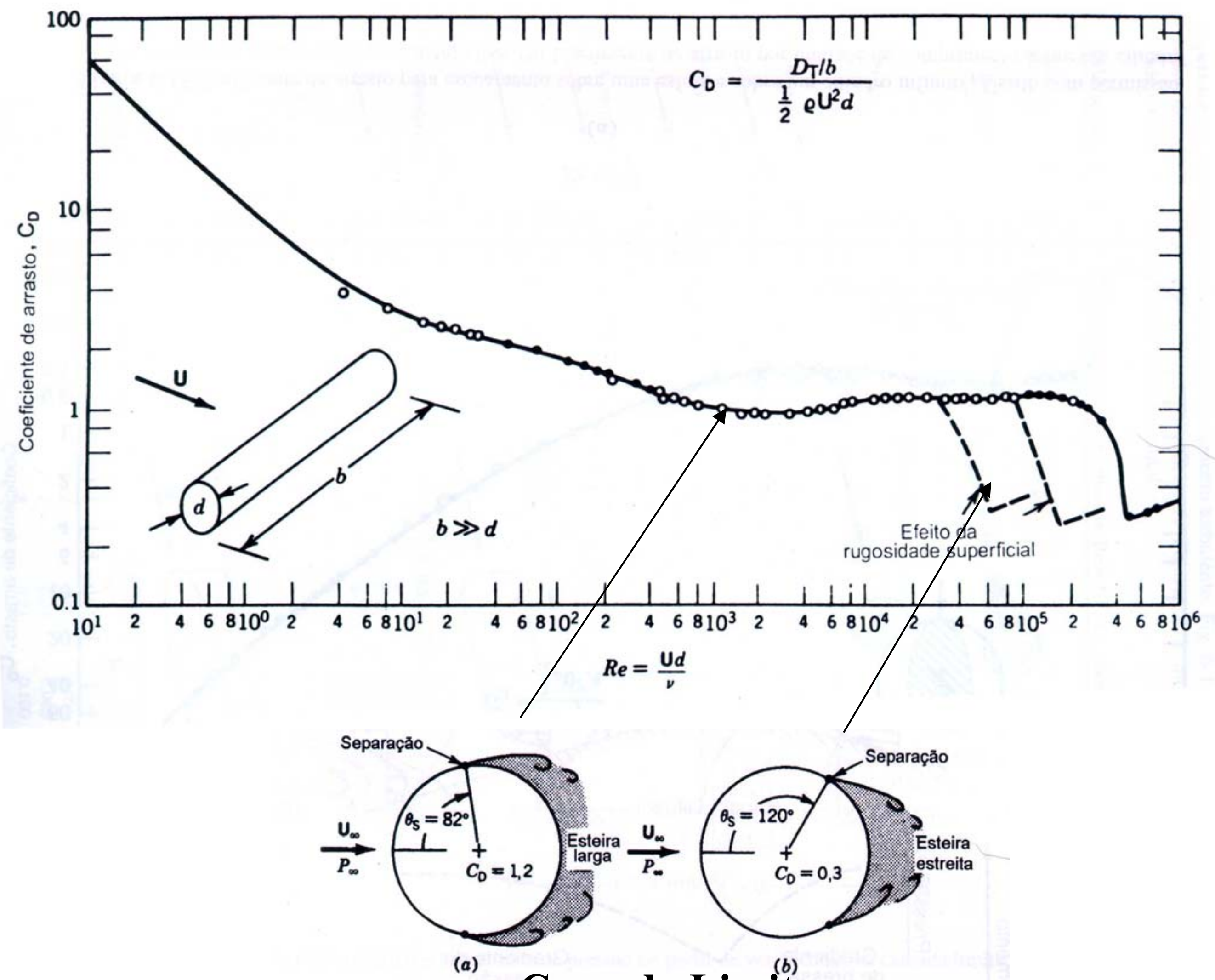


Figura 6-11 Pressão de escoamento e de superfície sobre um cilindro circular infinito normal ao escoamento. (a) Escoamento laminar, (b) Escoamento turbulento.

Arrasto de Forma
(Distribuicão de Pressão)



Camada Limite
(a) Laminar & (b) Turbulento

Drag

$$F_{D,\,friction} = C_{D,\,friction} \times \frac{1}{2}\rho V^2 A$$

$$F_{D,\,pressure} = C_{D,\,pressure} \times \frac{1}{2}\rho V^2 A$$

$$F_{D,\,total} = F_{D,\,pressure} + F_{D,\,friction}$$

Arrasto Total

O arrasto de forma e o viscoso constituem os dois mecanismos que causam a força de arrasto num corpo.

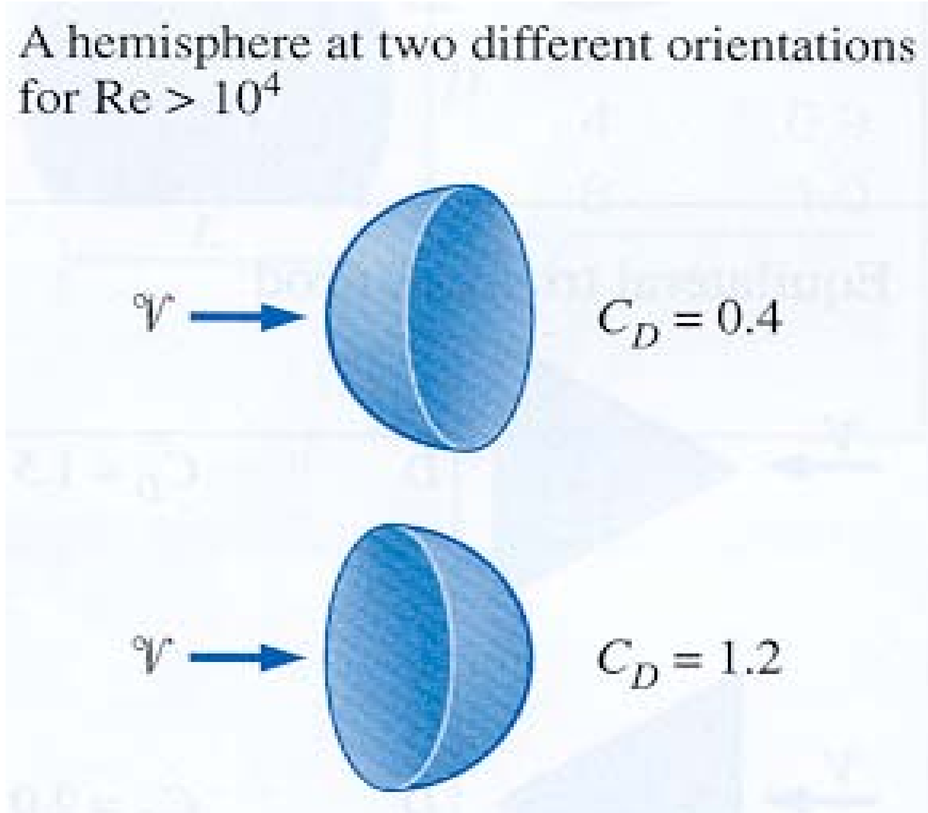
$$\overline{D}_T = \overline{D}_P + \overline{D}_f$$

Arrasto Total	Arrasto Forma	Arrasto Viscoso

$$C_D = \frac{\overline{D}_T}{(1/2)\rho U_{ext}^2 \cdot A}$$

Drag

- ***Drag is very geometry dependent.***
- ***Tables 13-1 and 13-2 have drag coefficients for some common shapes.***

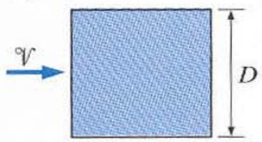


Movie: Geometry Drag DependencyDrag

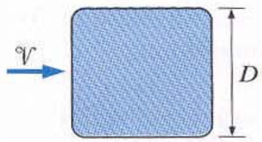
TABLE 13-1

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length normal to the direction of the paper (for use in the drag force relation $F_D = C_D A \rho \mathcal{V}^2/2$ where $\mathcal{V}$ is the free-stream velocity away from the body)

Square rod

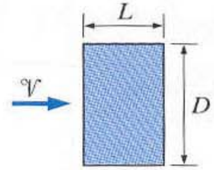


Sharp corners:
$C_D = 2.2$



Round corners
($r/D = 0.2$):
$C_D = 1.2$

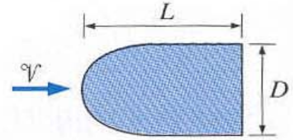
Rectangular rod



Sharp corners:

L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

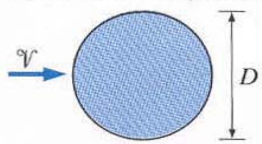
*Corresponds to thin plate



Round front edge:

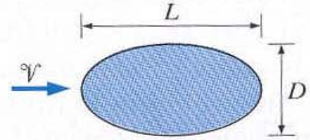
L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

Circular rod (cylinder)



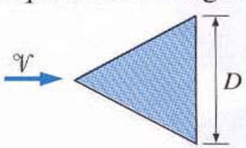
Laminar:
$C_D = 1.2$
Turbulent:
$C_D = 0.3$

Elliptical rod

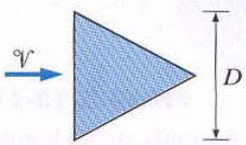


	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

Equilateral triangular rod

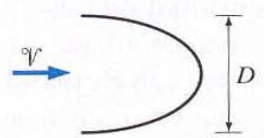


$C_D = 1.5$

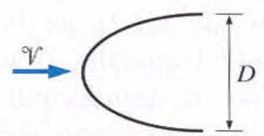


$C_D = 2.0$

Semicircular shell

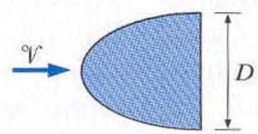


$C_D = 1.2$

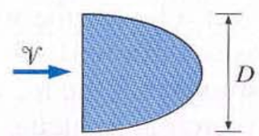


$C_D = 2.3$

Semicircular rod



$C_D = 1.2$



$C_D = 1.7$

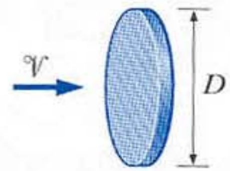
TABLE 13-2

Representative drag coefficients C_D for various three-dimensional bodies for Re > 10^4 based on the frontal area (for use in the drag force relation $F_D = C_D A \rho \mathcal{V}^2/2$ where $\mathcal{V}$ is the free-stream velocity away from the body)

Cube, $A = D^2$

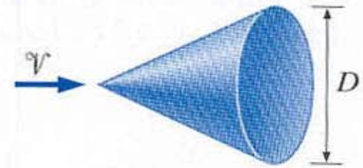
$C_D = 1.05$

Thin circular disk, $A = \pi D^2/4$



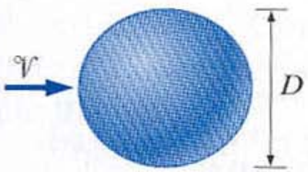
$C_D = 1.1$

Cone (for $\theta = 30°$), $A = \pi D^2/4$



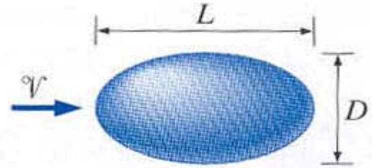
$C_D = 0.5$

Sphere, $A = \pi D^2/4$



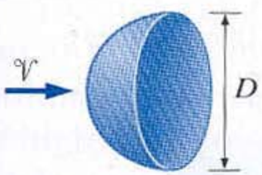
Laminar:
$C_D = 0.5$
Turbulent:
$C_D = 0.2$

Ellipsoid, $A = \pi D^2/4$

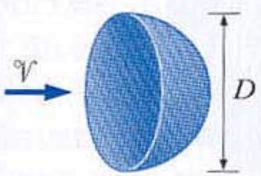


	C_D	
L/D	Laminar	Turbulent
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

Hemisphere, $A = \pi D^2/4$

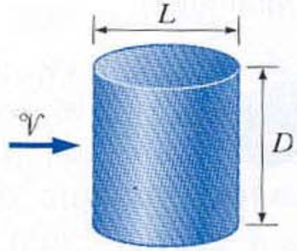


$C_D = 0.4$



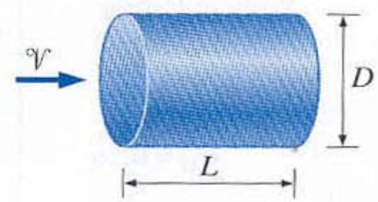
$C_D = 1.2$

Short cylinder, vertical, $A = \pi D^2/4$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9

Short cylinder, horizontal, $A = \pi D^2/4$



L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

TABLE 13-2 *(Concluded)*

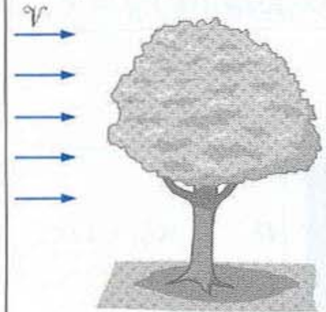
Streamlined body, $A = \pi D^2/4$

$C_D = 0.04$

Parachute, $A = \pi D^2/4$

$C_D = 1.3$

Tree, A = frontal area



$\mathcal{V}$, m/s	C_D
10	0.4–1.2
20	0.3–1.0
30	0.2–0.7

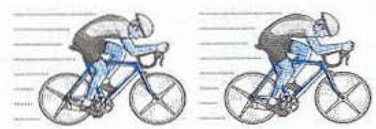
Person (average)

Standing, $C_D A = 9\ \text{ft}^2 = 0.84\ \text{m}^2$

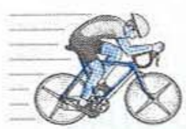
Sitting, $C_D A = 6\ \text{ft}^2 = 0.56\ \text{m}^2$

Bikes

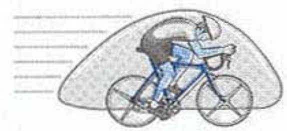
Upright: $A = 5.5\ \text{ft}^2 = 0.51\ \text{m}^2$, $C_D = 1.1$



Drafting: $A = 3.9\ \text{ft}^2 = 0.36\ \text{m}^2$, $C_D = 0.50$



Racing: $A = 3.9\ \text{ft}^2 = 0.36\ \text{m}^2$, $C_D = 0.9$



With fairing: $A = 5.0\ \text{ft}^2 = 0.46\ \text{m}^2$, $C_D = 0.12$

Semitruck, (A = frontal area)

Without fairing: $C_D = 0.96$

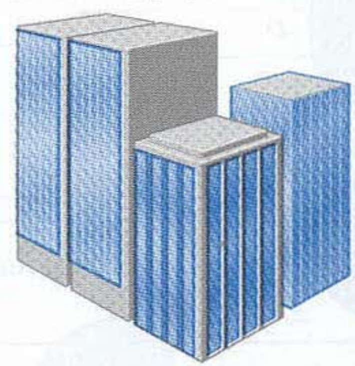
With fairing: $C_D = 0.76$

Automotive (A = frontal area)

Minivan, $C_D = 0.4$

Passenger car, $C_D = 0.3$

High-rise buildings (A = frontal area)



$C_D = 1.4$

Tabela 6-3 Coeficientes de arrasto de objetos bidimensionais para Re ≈ 10^5

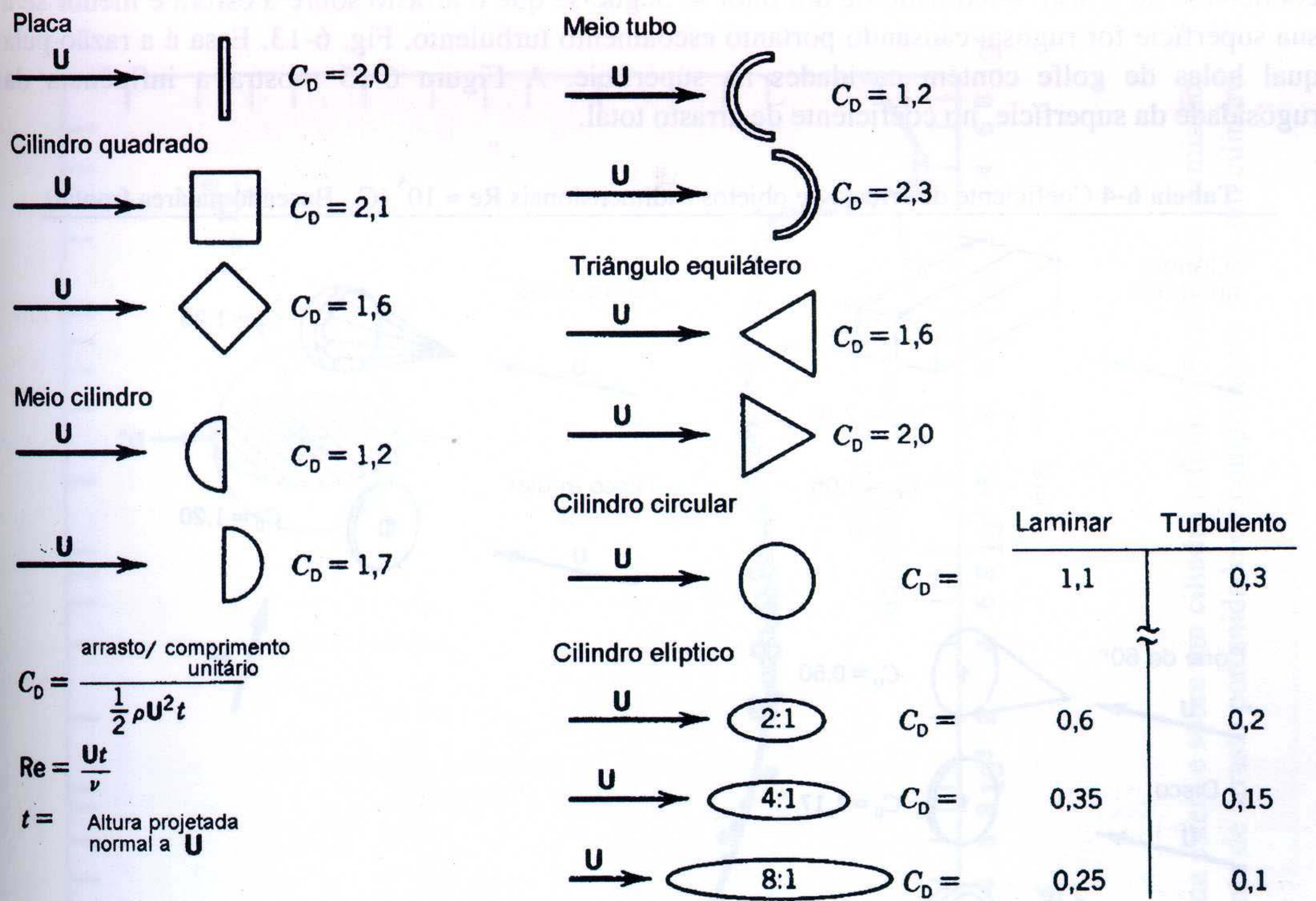
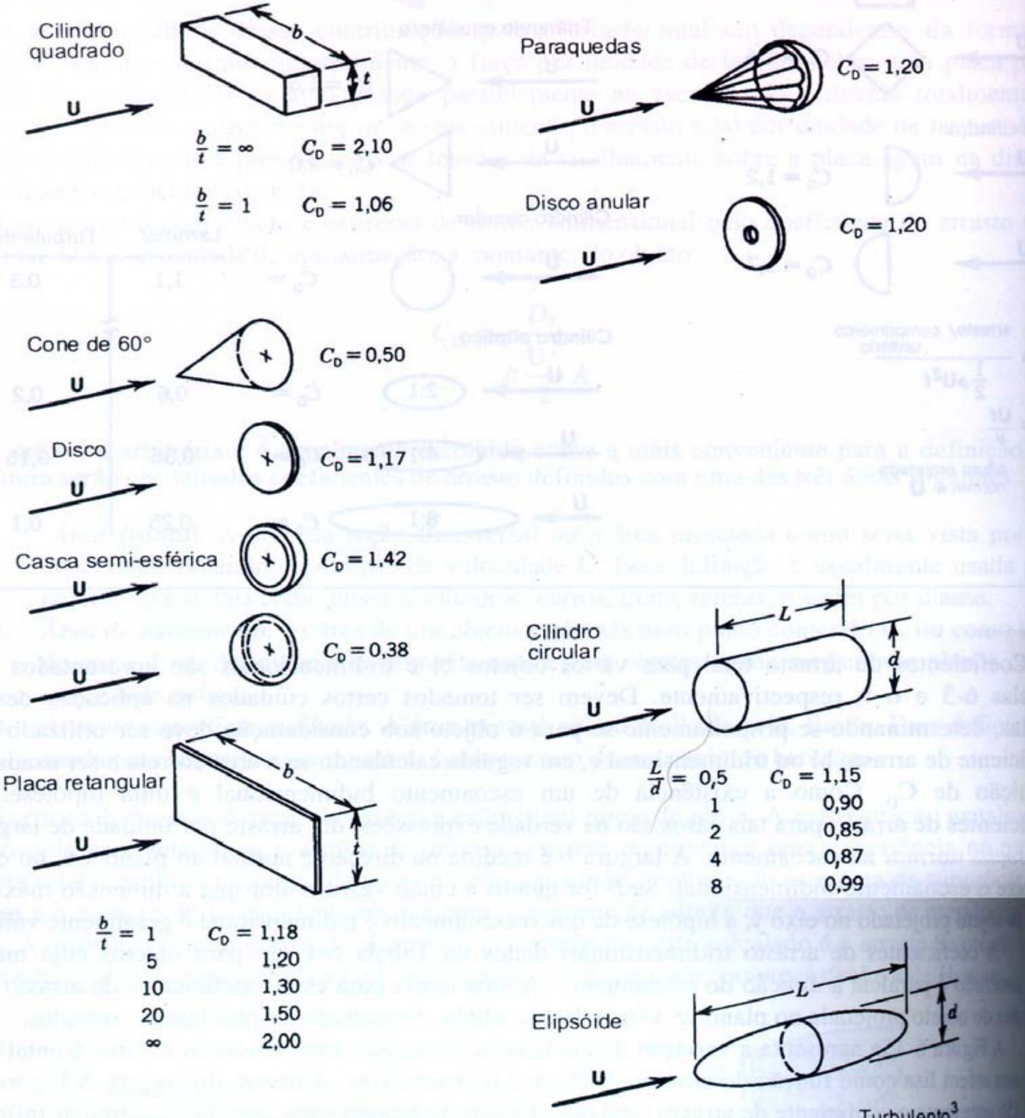


Tabela 6-4 Coeficiente de arrasto de objetos tridimensionais $Re \approx 10^5$ (C_D Baseado na área frontal)



Cilindro quadrado

$\frac{b}{t} = \infty$ $C_D = 2,10$

$\frac{b}{t} = 1$ $C_D = 1,06$

Paraquedas $C_D = 1,20$

Disco anular $C_D = 1,20$

Cone de 60° $C_D = 0,50$

Disco $C_D = 1,17$

Casca semi-esférica $C_D = 1,42$

$C_D = 0,38$

Cilindro circular

L/d	C_D
0,5	1,15
1	0,90
2	0,85
4	0,87
8	0,99

Placa retangular

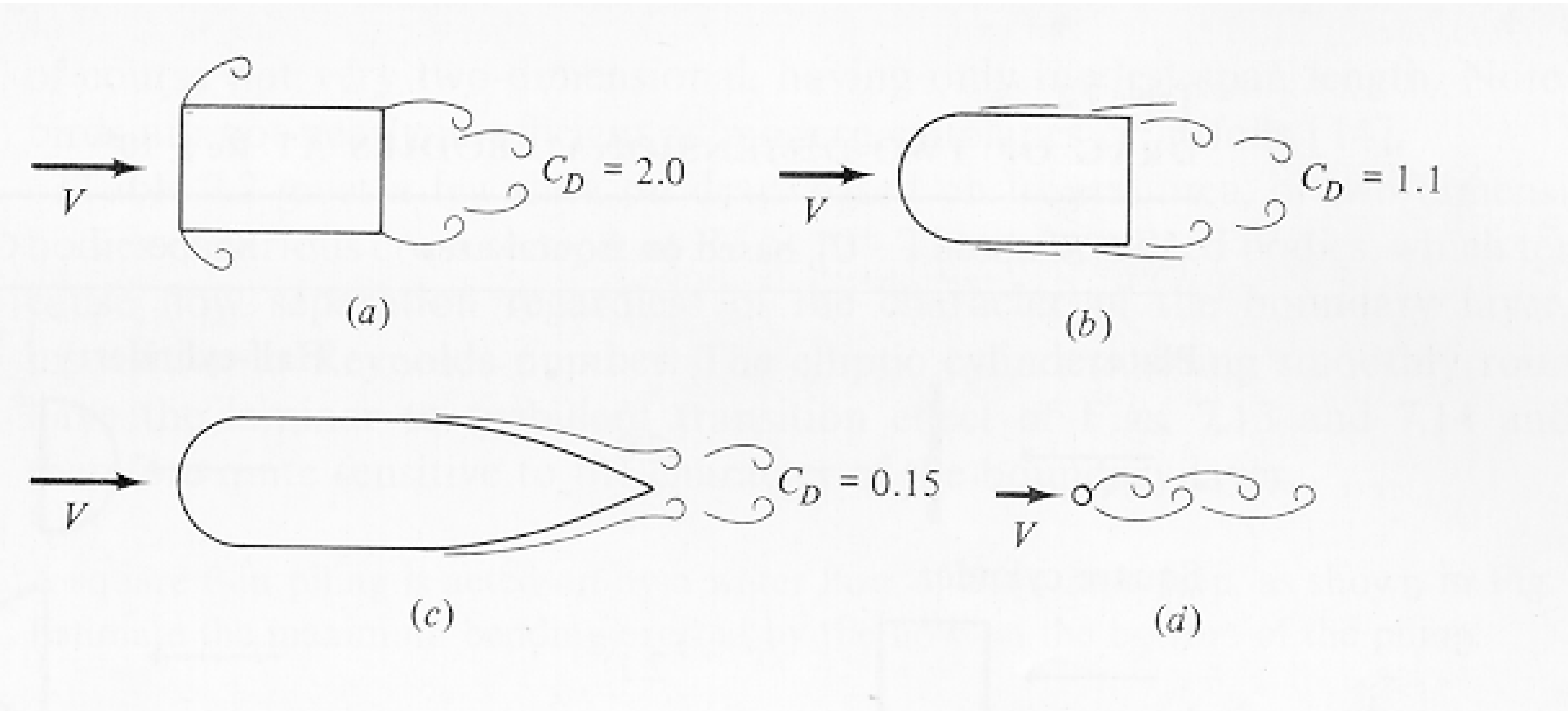
b/t	C_D
1	1,18
5	1,20
10	1,30
20	1,50
∞	2,00

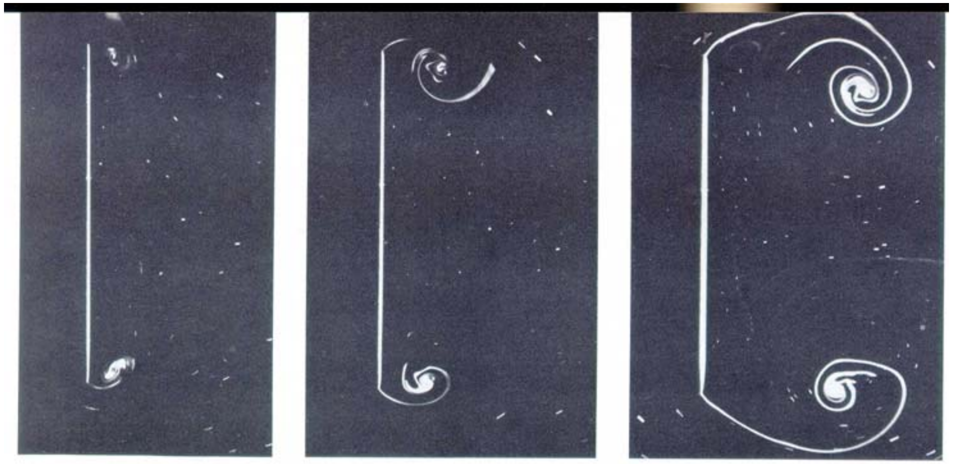
Elipsóide

L/d	Laminar C_D	Turbulento[3] $Re_L \approx 10^6$	Turbulento[3] $Re_L \approx 10^7$
1	0,47	0,100	0,090
2	0,25	0,055	0,040
4	0,20	0,065	0,041
8	0,23	0,100	0,078

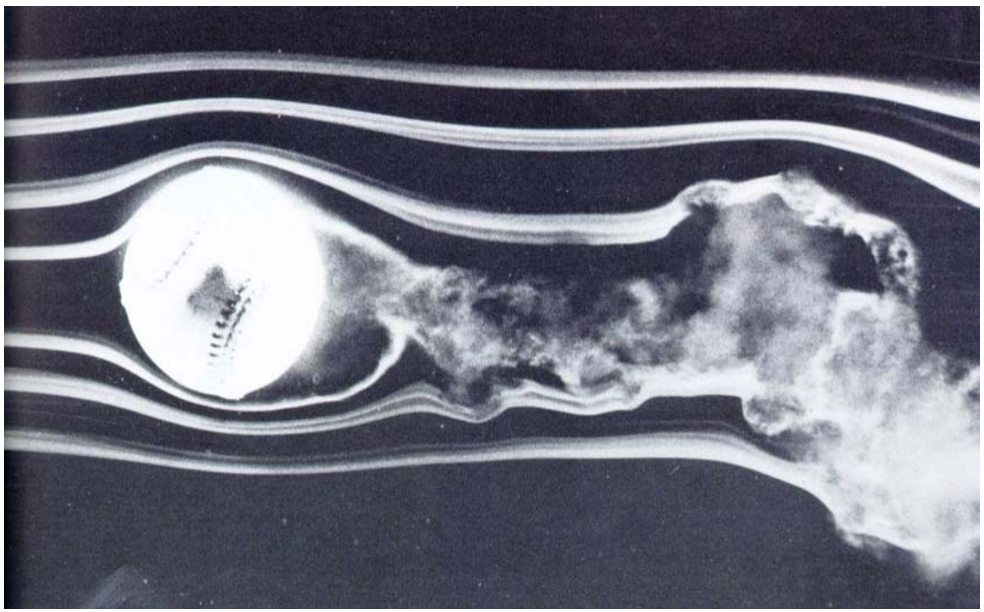
Re baseado em L ou t a altura projetada normal a U

A importância da forma aerodinâmica na redução do arrasto, C_D baseado na área frontal do corpo. (a) cilindro retangular; (b) c/ nariz arredondado; (c) c/ nariz e cauda arredondados e; (d) cilindro circular com o mesmo arrasto do caso (c) !





63. Impulsive motion of a flat plate normal to itself. The Reynolds number is 88 based on breadth. White dye generated on the plate by electrolysis of water shows a spiral vortex sheet shed from each edge. The plate has moved 0.079, 0.26, and 0.93 breadths. *Taneda & Honji 1971*



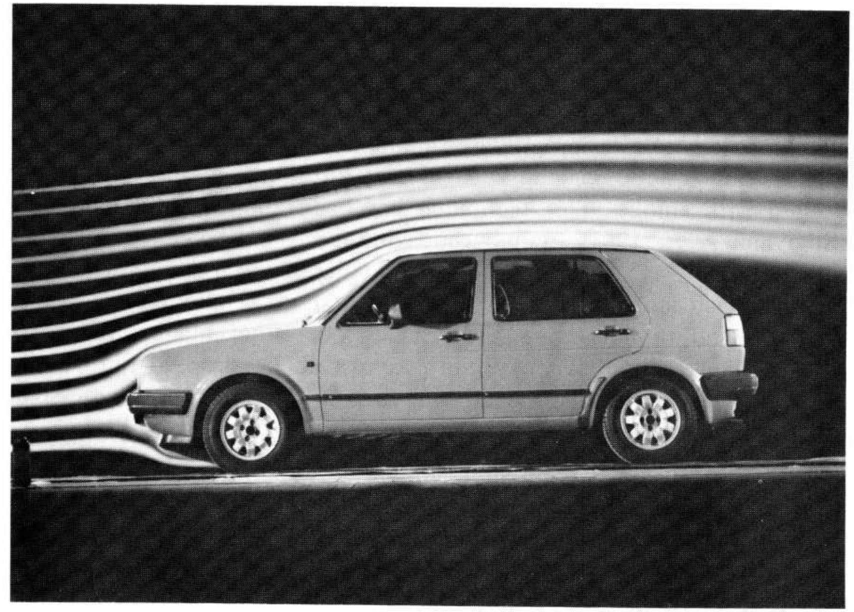


Fig. 2.13 Smoke lines around a road vehicle in a full-scale wind tunnel. (Courtesy of Volkswagenwerk AG.)

TEAMPLAY

- ***The drag coefficient of a vehicle increases when its window are rolled down or its sunroof is opened. A sports car has a frontal area of 2.04 m^2 and a drag coefficient of 0.32 when the windows and sunroof are closed. The drag coefficient increases to 0.41 when the sunroof is open. Determine the additional power consumption of the car at (a) 50 km/h and (b) 120 km/h when the sunroof is opened. Take the density of air to be 1.16 kg/m^3.***

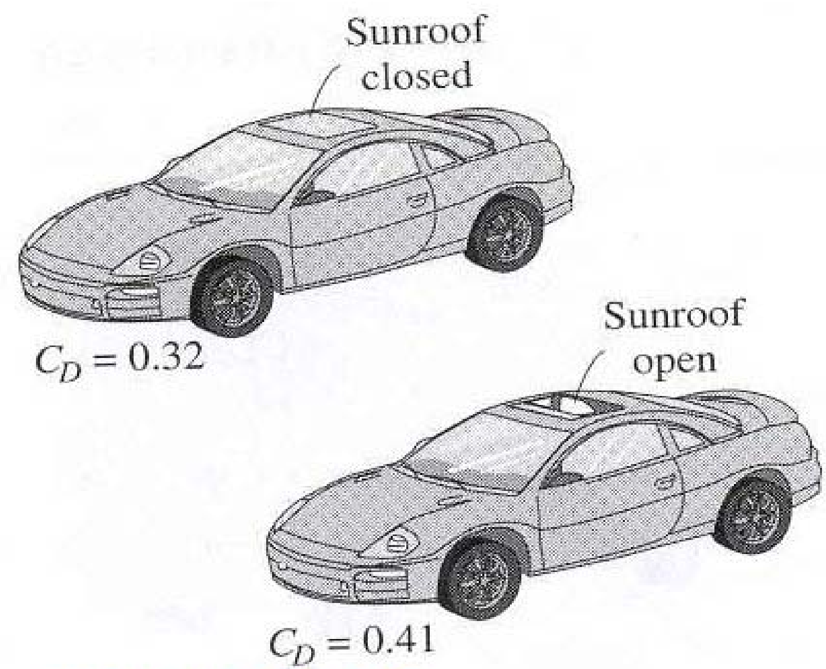


FIGURE P13-40E